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Modelling the vulnerability of *Taxus wallichiana* to climate change scenarios in South East Asia

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ABSTRACT

Taxus wallichiana (Himalayan yew) has been subjected to over-exploitation for its anti-cancer ingredient Taxol. As a consequence, the species has already become endangered, facing enhanced threats of regional extinction. To compound this, the species shows high vulnerability to climate change impacts that may significantly *reduce* its present climatic niche. In spite of the ecological and enormous commercial importance of the species, the direct or indirect impacts of climate change on the species are not yet well-researched and well-documented. To develop sustainable adaptation pathways to conserve the surviving populations of the species, it is important to have precise assessments of the future distribution ranges of the species. The present study models the potential current and future distribution ranges of *Taxus wallichiana* based on its suitable climatic envelop developed under a baseline scenario (1960–1990) and climate change scenarios centred on representative concentration pathways (RCPs) for the year 2070, as provided in the Fifth Assessment Report (AR5) of the UNO's Intergovernmental Panel on Climate Change (IPCC). The projected shrink in climatic niche of *Taxus wallichiana* by 28% (RCP 4.5) and 31% (RCP 8.5) highlights the vulnerability of the endangered species to climate change impacts and the perturbations on the structure of mountain ecosystem. It raises an alarm for immediate conservation of geographic areas that can provide potential refuge to the species under the adverse climate change impacts.

1. Introduction

Human-induced climate change is emerging as a challenge for the sustainability of biodiversity globally (Pereira, 2010). Several studies researching diverse ecosystems point to a changing interface of the existing biodiversity in terms of their structure and functioning under the influence of 21st-century climate change and habitat loss (Garcia et al., 2012; Sala et al., 2000; Thuiller et al., 2005). Mountain flora especially, is vulnerable to the rising temperature resulting from the emission of greenhouse gases on global and as well as regional scales. Global warming may induce species range expansions to higher elevation for sustaining their populations (Kharuk, 2007). Some studies based on the past and current changes in tree species richness and distributions have been testified across different mountain regions (Castro et al., 2004; Peñuelas et al., 2008; Telwala et al., 2013). The shift in the climatic envelop is expected to bring significant change in the habitat conditions of the resident species leading to changes in species richness, population structure and behaviour. This study is a detailed assessment of impacts of projected climate change on the distribution of an endangered and key medicinal tree species *Taxus wallichiana* which is already facing the threats of extinction.

Taxus wallichiana popularly known as Himalayan yew is an important medicinal species (Samant et al., 1998) which is extensively harvested for Taxol, a potent anti-cancer drug that has an extraordinary property of checking the development of carcinogenic cells. Taxol is extensively used for the treatment of various sorts of cancers and other diseases in modern medicine (Mukherjee et al., 2002; Phillips et al., 1998; Poupat et al., 2000; Wani et al., 1971). However, unchecked overexploitation of the species due to ever-increasing demand for Taxol has endangered the species (Cragg et al.,1993; Goldspiel, 1997) that has been listed in Appendix II of CITES (Convention on International Trade in Endangered Species of Wild Fauna and Flora; available from http://www.cites.org/eng/app/appendices.shtml#10). Nevertheless, the future of the species may be at great risk, as its worldwide population has undergone an alarming decline during the past 25 years due to overexploitation of natural resources and deforestation (Paul et al., 2013). As much as 90 per cent decline in its population has been reported in Indian Himalayas by the International Union for Conservation of Nature (IUCN; Thomas and Farjon, 2011). While overexploitation and deforestation are a major cause, the impressions of climate change on *Taxus*

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wallichiana is yet to be explored.

One of the methods to understand the impacts of climate change on species distribution is Species Distribution Modelling (SDM). It has become an effective practice for assessing potential vegetation shifts under new environmental conditions (Porfirio et al., 2014) in recent years. Species distribution provides a framework for the assessment of species population size in terms of species range areas. As a method, the SDM uses the characteristic relationship between ecological factors and known species event records to distinguish the natural conditions in which a population can be maintained (Pearson, 2007). For better calibration of these models, it is important to carefully set the extent of the study area as they can strongly influence the model results (Acevedo, 2012; Barve, 2011; Jiménez-Valverde, 2013). As a core strategy, this principle is also the baseline of different types of modelling techniques used in the present study. This approach can also be used effectively to indicate the potential changes in the ecosystem structure due to environmental changes in a given area of interest.

In the present study, we have used the new generation General Circulation Model (GCM) projections provided by the World Climate Research Programme (WCRP) based on the Intergovernmental Panel on Climate Change (IPCC)'s Fifth Assessment Report (AR5; Pachauri et al., 2014). Four major Representative Concentration Pathway (RCP) signifying different scenarios of climate change for 2100 are proposed. These RCP scenarios designate four different levels of radiative forcing i.e., 2.6, 4.5, 6.0 and 8.5 W/m^2 and are based on the assumptions about economic activity, energy sources, population growth and other socio-economic factors which are further reproduced with each GCM. The variability in the projected climate data occur due to the fluctuations in the modelled coupled exchanges among the components of the GCM's such as land, atmosphere, oceans and cryosphere (Deser et al., 2014).

In a nutshell, this study attempts to quantify the magnitude of climate change impacts on the distribution of *Taxus wallichiana*, using a baseline climate data (1960–1990) and projected climate change scenarios for two RCPs ranging over next 50 years in the Hindukush and South East Asia. As per the trends obtained, it is expected that the suitable habitat of *Taxus wallichiana* may reduce with the magnitude and direction of projected climate change. This research provides an insight into the response of a species in terms of its distribution to a suit of bioclimatic factors. The study can be used to serve the conservation goals like the management and in situ preservation of the species.

2. Materials and methods

2.1. Study area

Taxus wallichiana is distributed across most of its range through the Himalayas, China and South East Asia between elevation ranges from 900 to 3700 m. The study area consists of countries such as India, China [SE Xizang (Tibet), NW Yunnan, S Sichuan], Nepal, Bhutan, Myanmar, Vietnam, Malesia, Philippines and Thailand. The region can broadly be divided into tropical and sub-tropical zones characterized by three intermingled physical elements: mountain ranges, plains and plateaus. Localities at high altitudes comprising different mountain ranges in this region exhibit temperate and alpine climate. The study area receives an extensive and regular monsoonal weather system generating considerable annual precipitation. The region is distinctively rich in biodiversity (Myers et al., 2000). The projected change in the Annual Mean Temperature (MAT) in the study area under different climate change scenarios is shown in Fig. 1.

2.2. Species data

Species distribution modelling mainly consists of species occurrence data and climatic variables (Pearson, 2007). The species occurrence data used for this study was collected from online portals such as Global Biodiversity Information Facility (GBIF.org., 2016; https://www.gbif.org), field surveys, existing species records and herbaria. *Taxus wallichiana* is a rare and endangered species. Extensive field surveys were made in the study area and several other sources were checked for its location points. In order to check the credibility and quality of species occurrence data acquired from ancillary sources such as literature and herbaria, we further processed the data in R software. Duplicate or repeated occurrence points were removed and each occurrence point was overlaid with Digital Elevation Model (DEM) for topographic information and validation.

2.3. Climate data

The climate data were downloaded and processed from WorldClim database- http://www.worldclim.org/ (Hijmans et al., 2005). The monthly observations of temperature and precipitation are derived using the topographic information such as latitude, longitude and elevation of a region as statistical predictor variables with the help of weighted linear regression approach. WorldClim provides grid based current (baseline) and projected climate data for 2070 at 30 arc-seconds spatial resolution. The current data are the monthly average for thirty years spanning from 1960 to 1990. We have utilized nineteen bioclimatic layers that are developed from the monthly temperature and precipitation data, keeping in mind the research goal to have relevant environmental data and more biologically meaningful information as predictor variables (Table 1). In general, a suite of GCM combinations to project future climate is recommended (Lutz et al., 2010). For mapping the suitable climatic envelop of *Taxus wallichian*a under climate change impact, we used data from three Global Climate Models- GFDL-CM3 (Griffies et al., 2011), MRI CGCM3 (Yukimoto et al., 2012) and CNRM CM5 (Voldoire et al., 2013) for RCP 4.5 (Wise et al., 2009) and RCP 8.5 (Riahi et al., 2011) climate change scenarios (2070). RCP 4.5 is a stabilization scenario in which total radiative forcing is stabilized shortly after 2100, without overshooting the long-run radiative forcing target level. On the other hand, RCP 8.5 is characterized by increasing greenhouse gas emissions over time that will lead to high greenhouse gas concentration levels. The topographic feature aspect, extracted from Digital Elevation Model (DEM) at the spatial resolution of ~90 m generated from Shuttle Radar Topography Mission (SRTM) available at http://srtm.csi.cgiar. org was also used in the modelling (Jarvis et al., 2008).

2.4. Climatic envelope model design

The freely available 'biomod2' package in R software for modelling the climatic envelope of *Taxus wallichiana* provides a modelling platform for ensemble estimate of species distributions, offering a range of methods and approaches for exploration of species-environment relationships (Thuiller, 2003) in any temporal and spatial domain (current, past and future). The modelling methods available in the biomod2 package are as follows: Generalized Linear Models (McCullagh and Nelder, 1989), Generalized Additive Models (Hastie and Tibshirani, 1990), Generalised Boosted Models (Ridgeway, 1999), Classification and Regression Tree analysis (Breiman et al., 1984), Artificial Neural Networks (Venables and Ripley, 2002), Surface Range Envelope (Busby, 1991), Flexible Discriminant Analysis (Hastie et al., 1994), Multiple Adaptive Regression Splines (Friedman, 1991), Random Forest (Breiman, 2001) and Maxent (Berger et al., 1996).

We use all the nineteen bioclimatic layers and aspects as predictor variables to build the initial models. On the basis of importance value of predictors and Pearson's correlation coefficient between the predictor variables, final seven variables – BIO4, BIO5, BIO10, BIO11, BIO14, BIO16 and aspect were selected for building the final models. Pearson's correlation coefficient is used to avoid multicollinearity (Dormann et al., 2013) among the variables. For model calibration and evaluation, 75 per cent data for model training and 25 per cent data for model-testing were kept. To simplify the computation, background samples

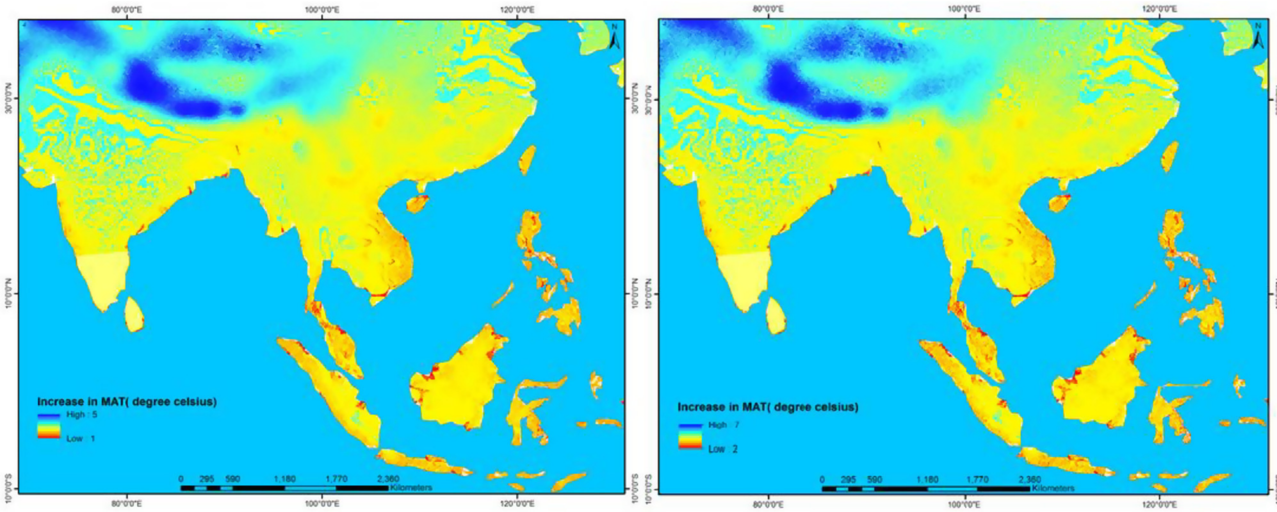

Fig. 1. Projected change in the Annual Mean Temperature (C°) in the study area under climate change scenarios (a) RCP4.5 (b) RCP 8.5 in 2070. ; Source: www.worldclim.orgHijmans et al. (2005).

generated randomly in R, representing the scope of natural conditions in the modelled region were used. These samples arrange for a sample of the set of available environmental settings in the region. Subsequent to this, models were run with five replications each. Model performance was tested using Receiver Operating Characteristic (ROC) and True Skill Statistic (TSS) scores. All the models were included in the ensemble model as each model performed above average (AUC > 0.75). For statistical analysis, such as the scatter plots, response curves and projected percentage change in the area of climatic niche for *Taxus wallichiana*, we have used distribution probability above 0.5 (Li, 1997; Stockwell and Peterson, 2002). A brief approach to the study is given in Fig. 2.

3. Results

The model outputs of the two IPCC future scenarios as well as the current modelled species distribution were modelled using the ensemble species distribution model.

3.1. Model evaluation

The models evaluation scores using ROC and TSS scores shows that overall, the predicted distributions on both calibration and evaluation data showed concurrence with observed distributions (Fig. 3). According to the TSS/ROC scores, RF performed best in all the ten models while SRE received the lowest scores. GLM, GBM, and MAXENT. Tsuruoka have also performed fairly well in modelling the results. The ROC, characterised by the Area under Curve (AUC) is distributed between values ranging from 0 to 1 (Wiley et al., 2003). Values measured > 0.9 are considered high, 0.7–0.9 moderate, 0.5–0.7 low and < 0.5 no better than random (Phillips et al., 2006).

3.2. Predictor variables and probability distribution of *Taxus wallichiana*

Predictor variable importance was computed to test the importance of predictor variables on the climatic niche of *Taxus wallichiana* (Fig. 4) using a simple correlation. The principle at work here is to generate model predictions by shuffling a single variable among the set of variables of the given dataset and measure the simple correlations between references, predictions and the shuffled variable. The return

Table 1
Environmental variables used for distribution modelling of *Taxus wallichiana* (Hijmans et al., 2005).

Category	Variable name	Abbreviation	Unit	Resolution/Scale
Bioclimatic variable Available from http://www.worldclim.org/	Annual Mean Temperature	BIO 1	°C	30 arc seconds
	Mean Diurnal Range	BIO 2	°C	30 arc seconds
	Isothermality (BIO 2/BIO 7) (×100)	BIO 3	Dimensionless	30 arc seconds
	Temperature Seasonality (Standard Deviation × 100)	BIO 4	Percent	30 arc seconds
	Max Temperature of Warmest Month	BIO 5	°C	30 arc seconds
	Min Temperature of Coldest Month	BIO 6	°C	30 arc seconds
	Temperature Annual Range (BIO 5-BIO 6)	BIO 7	°C	30 arc seconds
	Mean Temperature of Wettest Quarter	BIO 8	°C	30 arc seconds
	Mean Temperature of Driest Quarter	BIO 9	°C	30 arc seconds
	Mean Temperature of Warmest Quarter	BIO 10	°C	30 arc seconds
	Mean Temperature of Coldest Quarter	BIO 11	°C	30 arc seconds
	Annual Precipitation	BIO 12	mm	30 arc seconds
	Precipitation of Wettest Month	BIO 13	mm	30 arc seconds
	Precipitation of Driest Month	BIO 14	mm	30 arc seconds
	Precipitation Seasonality (Coefficient of Variation)	BIO 15	Dimensionless	30 arc seconds
	Precipitation of Wettest Quarter	BIO 16	mm	30 arc seconds
	Precipitation of Driest Quarter	BIO 17	mm	30 arc seconds
	Precipitation of Warmest Quarter	BIO 18	mm	30 arc seconds
	Precipitation of Coldest Quarter	BIO 19	mm	30 arc seconds
Topographic feature	Aspect		Degree	90 m

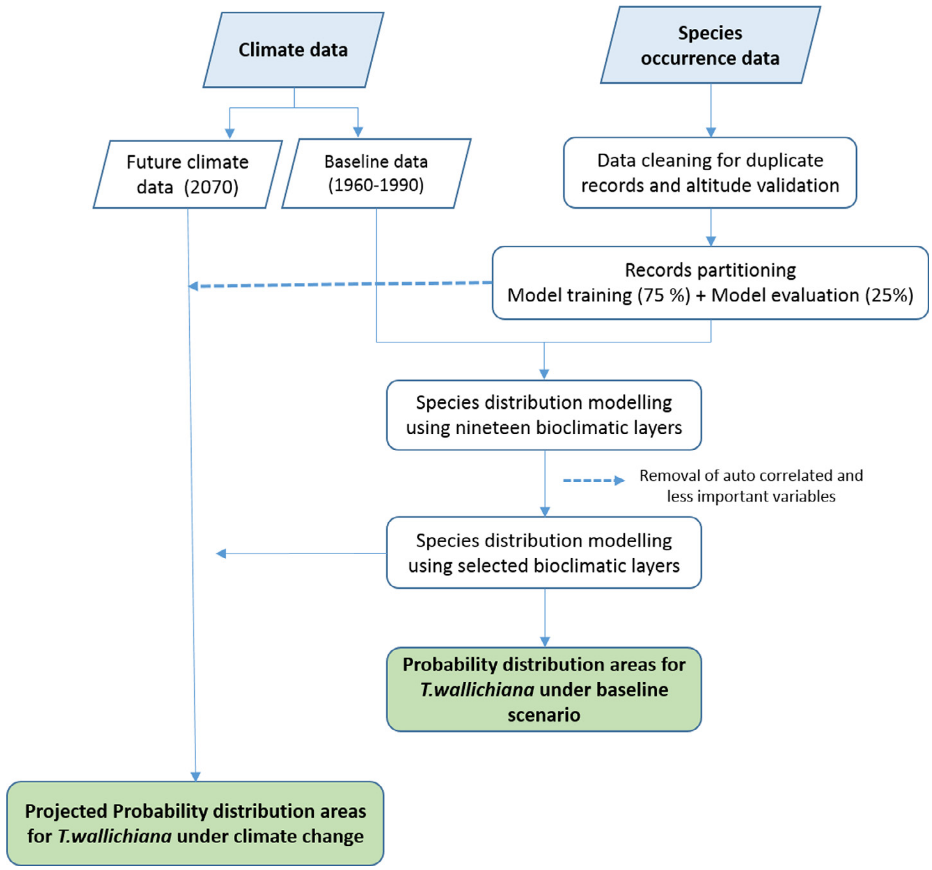

Fig. 2. Flowchart of the methodology.

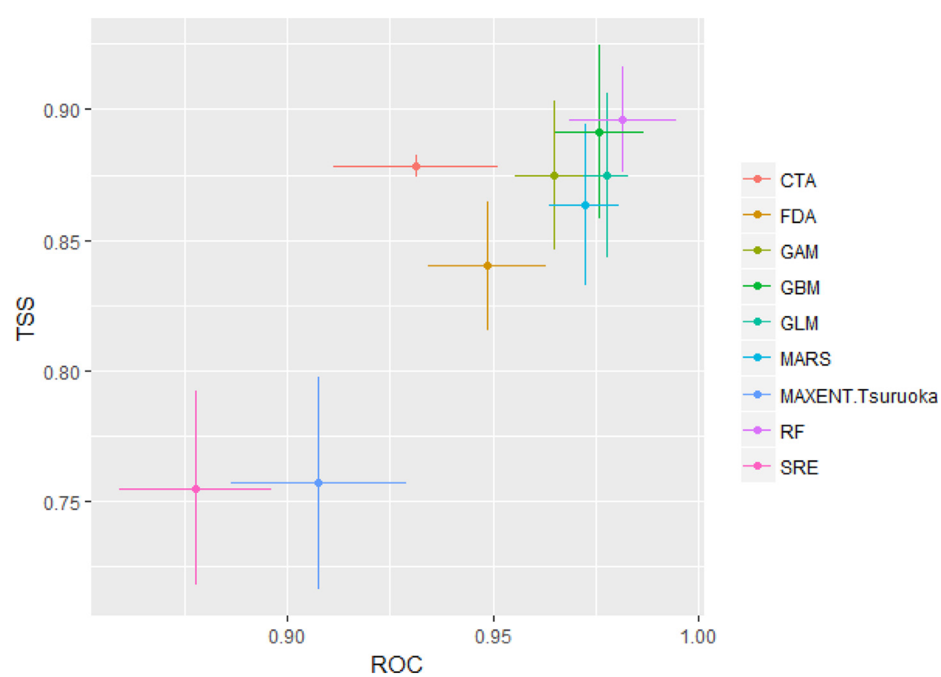

Fig. 3. Evaluation scores (ROC/TSS) of the individual models used in the ensemble modelling.

score is calculated by subtracting the computed simple correlation values with 1. The highest the value, the more influence the variable has on the model. The probability distribution of *Taxus wallichiana* is affected by both precipitation and temperature variables. Mean temperature of the coldest quarter (BIO11) shows the highest contribution to the probability distribution of *Taxus wallichiana* (Fig. 4). Other variables like mean temperature of the warmest quarter (BIO10), maximum temperature of the warmest month (BIO5) and precipitation of driest month also show high influence on the probability distribution of *Taxus wallichiana*.

Scatter plots were used to analyse the probability distribution of *Taxus wallichiana* with predictor variables (Fig. 5). It can be observed

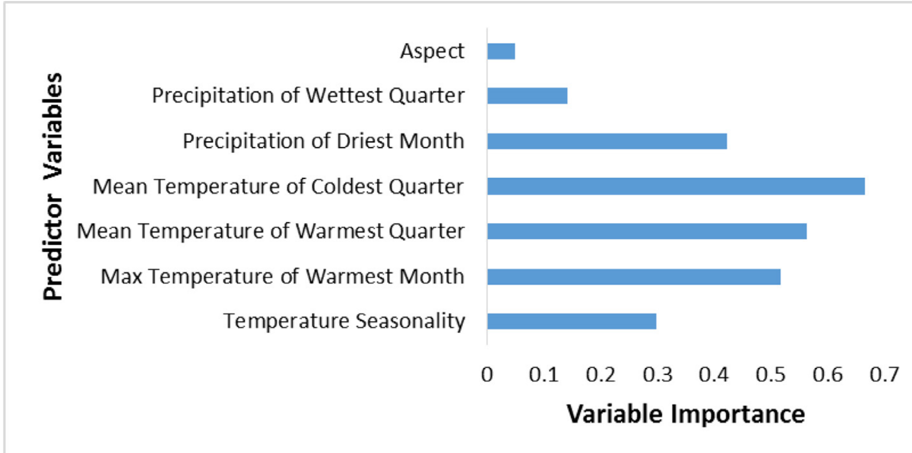

Fig. 4. Variable importance value of predictor variables used in the ensemble modelling.

that probability distribution of *Taxus wallichiana* is high in the regions with cooler summers and heavy precipitation.

For a better representation of predictor- probability relationship, 3D response curves were also plotted in the model independently of the algorithm used for building the model (Fig. 6). The figure demonstrates that the predictor variables such as BIO14, BIO5 and aspect show steep slopes with prediction probability, representing the sensitivity of these variables.

3.3. Model projections

The probable climatic niche modelled for *Taxus wallichiana* for the baseline scenario shows its presence in Himalayas, South East China and South East Asia (Fig. 7). Here, the high probability areas of the

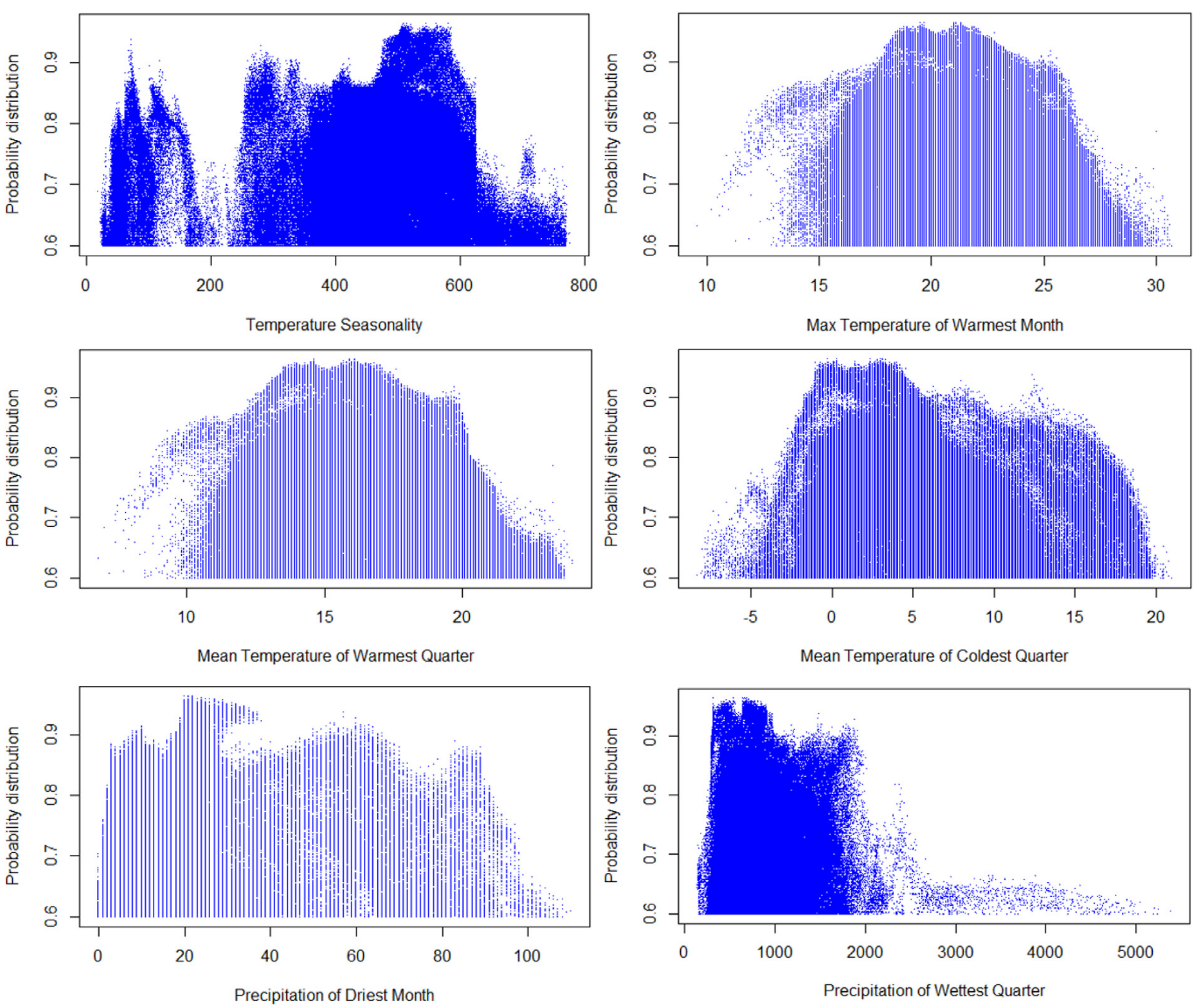

Fig. 5. Scatter plots between predictor variables and probability distribution of *Taxus wallichiana* under baseline climate scenario.

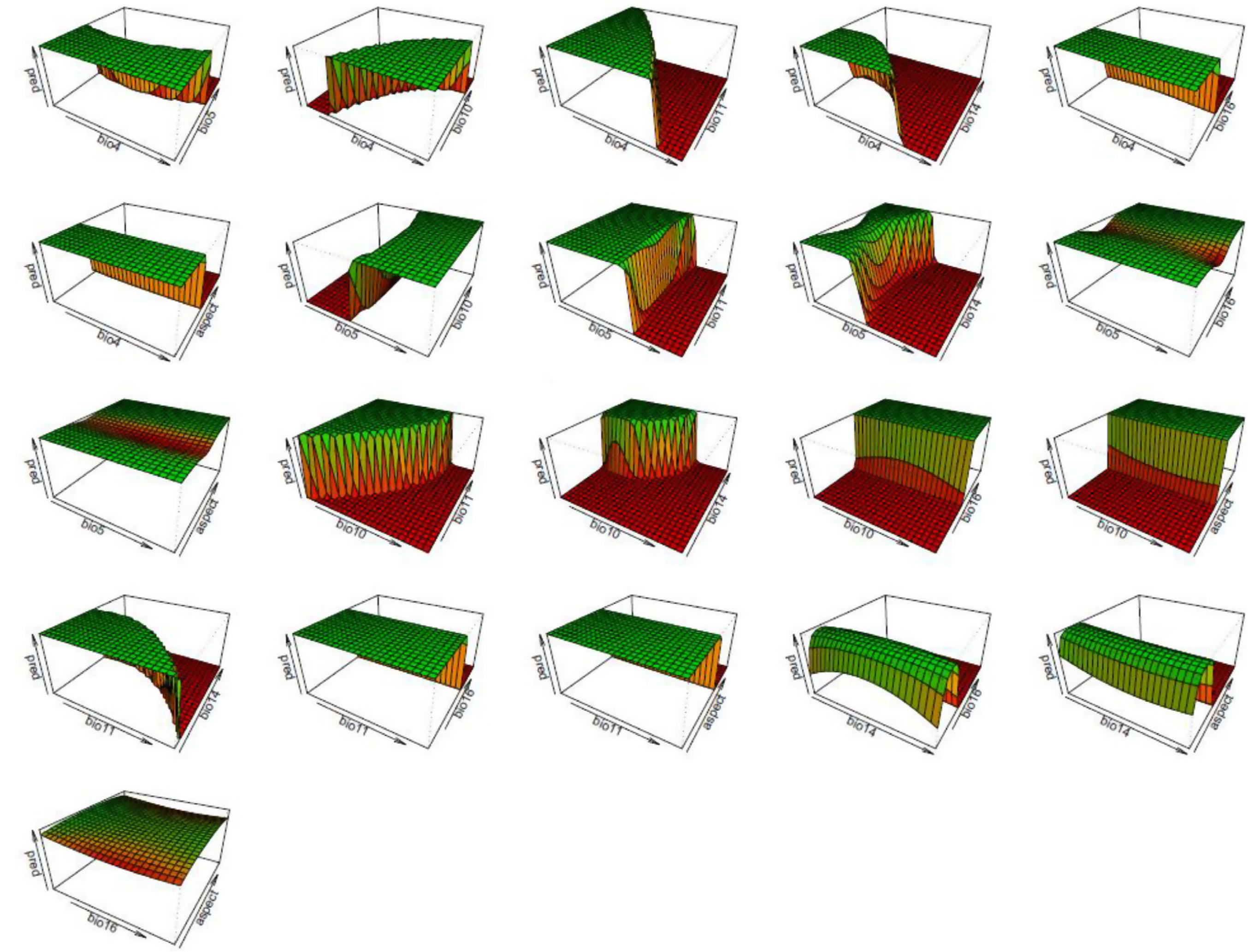

Fig. 6. Response curves showing the relationship between the probability distribution of *Taxus wallichiana* and predictor variables.

species can be found in Himalayan region of India, Nepal and Bhutan, Chinese provinces of Xizang, Sichuan, Guizhou and Yunnan, south-eastern countries like Vietnam, Laos, Myanmar, Philippines, Malaysia, Indonesian islands of Sulawesi, Sumatra, Jawa, Bali and Nusa tenggara. In the Himalayan region, a substantial portion of suitable climatic envelop of *Taxus wallichiana* can be recognized, occupying montane temperate forests (Champion and Seth, 1968, Pant and Samant, 2008). Mountainous terrain of South East China also harbours a significant size of suitable habitat for *Taxus wallichiana.* In South East Asia, the species can be found in limited extent, inhibiting the submontane forests spread across islands and mainland.

Under both scenarios of climate change – RCP 4.5 and 8.5, there is a steady decline in the suitable climatic habitat of *Taxus wallichiana* (Fig. 8). The species displays a significant response to expected climate change in terms of shrinkage in its climatic niche from low and mid-altitude montane regions. The change is more apparent in the Himalayan and South East China region. The results also show an upward shift in the probability distribution of *Taxus wallichiana* towards higher elevations under each climate change scenario.

In the case of RCP 4.5, the climatic niche of *Taxus wallichiana* shows a reduction of 28% in its climatic niche by 2070 as compared to its baseline scenario. Whereas under the climate change scenario of 8.5, it is expected to be around 31% in the study area. The regional analysis of the distribution results shows that the projected loss in the climatic niche of *Taxus wallichiana* in South East Asia and Hindukush and China is relatively severe in RCP 8.5 (Fig. 9). However, the trend is being contradicted in Himalayan region as the percentage loss in the climatic niche is higher in RCP 4.5 in the region (Fig. 9). Nonetheless, a steady shift in the climatic niche in the *Taxus wallichiana* towards Tibetan plateau is consistent under each climate change scenario.

4. Discussion

4.1. Ecology of Taxus wallichiana

Taxus wallichiana is a drought-sensitive species that prefers to grow under abundant rainfall and cold temperate montane and submontane climate regimes (Thomas and Lianming, 2013). When bioclimatic factors were associated with the distribution of *Taxus wallichiana,* mean temperature of both summer and winter season and precipitation of driest quarter performed strongly to influence its distribution. The species demonstrates strong response towards temperature and is observed to edge majority of its distribution to the areas having low/moderate summer temperature coupled with ample rainfall (Figs. 5 and 6). These areas are characterised by the presence of dense moist temperate montane forests and sub-montane forests. According to the baseline scenario maps, most of the predicted climatic niche of the *Taxus wallichiana* is distributed on the north facing slopes (Thomas and Lianming, 2013) with a mean elevation of 2672 m. The mountains on the north facing slope suffer less insolation and have sufficient moisture supply throughout the year from the snow cover (Maren et al., 2015).

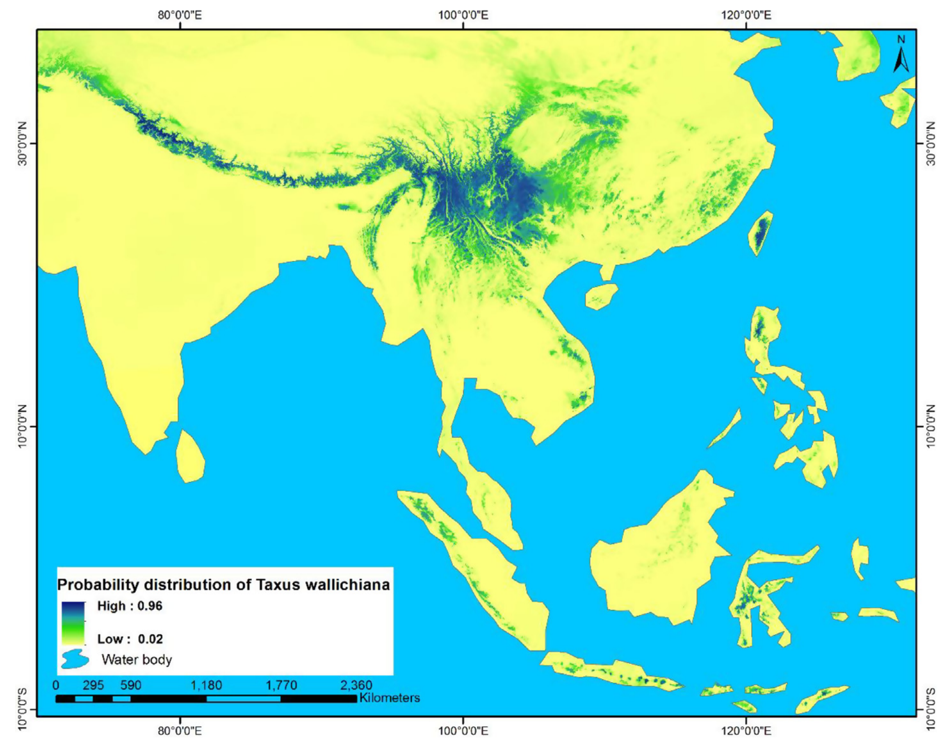

Fig. 7. Probability presence for *Taxus wallichiana* in the study area under baseline scenario (for the climate period of 1960–1990).

4.2. Baseline and climate change associated habitat loss

The results obtained in our study point to adverse consequences the climate change may have on the distribution size of *Taxus wallichiana.* The species shows a significant response to climate change under each climate change scenario, RCP 4.5 as well as RCP 8.5 in terms of range loss (Fig. 9). The climate change is probably going to modify future species distributions (Grabherr, 1994; Lutz et al., 2010; Nogués-Bravo et al., 2014; Pauli et al., 1996). These developments are likely to vary with GCM projections and the region. The loss in the climatic niche of *Taxus wallichiana* can be explained by the warming of lower elevation areas where the species can be currently found. Different aspects of climate change such as increase in temperature, retreating glaciers, extreme precipitation events, draughts (Xu et al., 2009) may induce disruptions in the physiology of *Taxus wallichiana*. Contrary to prospects, RCP 8.5 scenario is found to be more favourable for *Taxus wallichiana* as compared to RCP 4.5 scenario in the Himalayan region. This could be attributed to a relatively favourable warming projected at higher elevations under RCP 8.5 as compared to RCP 4.5 providing scope of expanding its current range in the region. The trend is limited in the montane areas of South East China and countries in South East Asia possibly due to higher treelines in these mountain ranges (Schickhoff, 2005; Shi and Who, 2013), offering not as much of geographical space for species range expansion. Thus, the transforming climatic conditions at higher elevations along the current distribution of *Taxus wallichiana* represent the potential areas that may evolve into suitable habitats for the species under climate change scenarios. Overall, the threats of climate change in conjugation with other anthropogenic pressures such as land use-land changes (Piovesan, 2009), resource exploitation (Purohit et al., 2001), diseases and species invasions pose an increased threat to the remaining population of *Taxus wallichiana.*

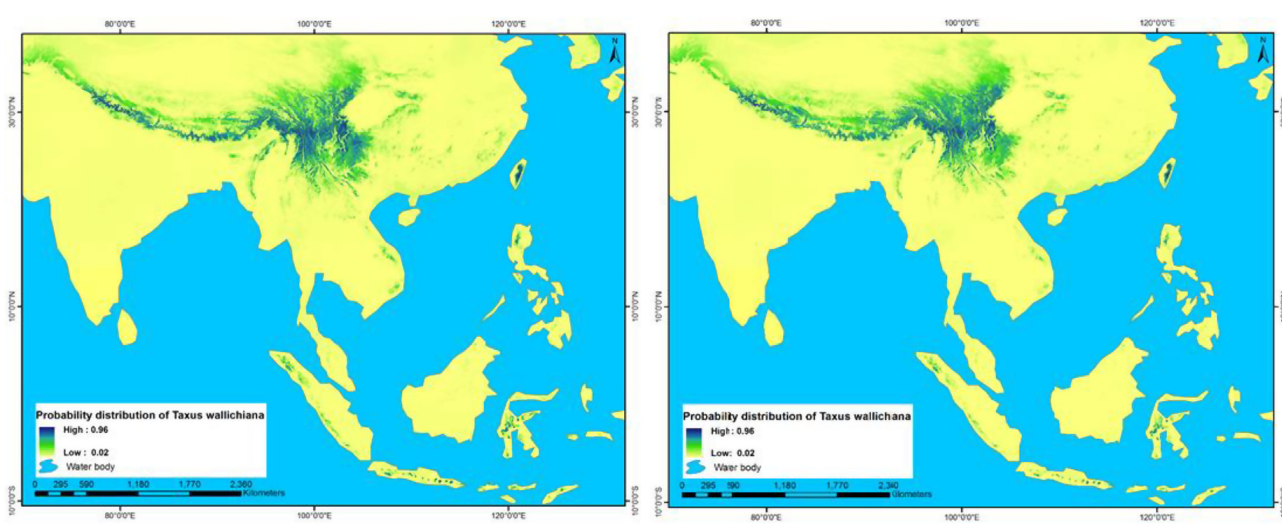

Fig. 8. Climatic niche projections for *Taxus wallichiana* under climate change scenarios of (a) RCP 4.5 and (b) RCP8.5 for the year 2070.

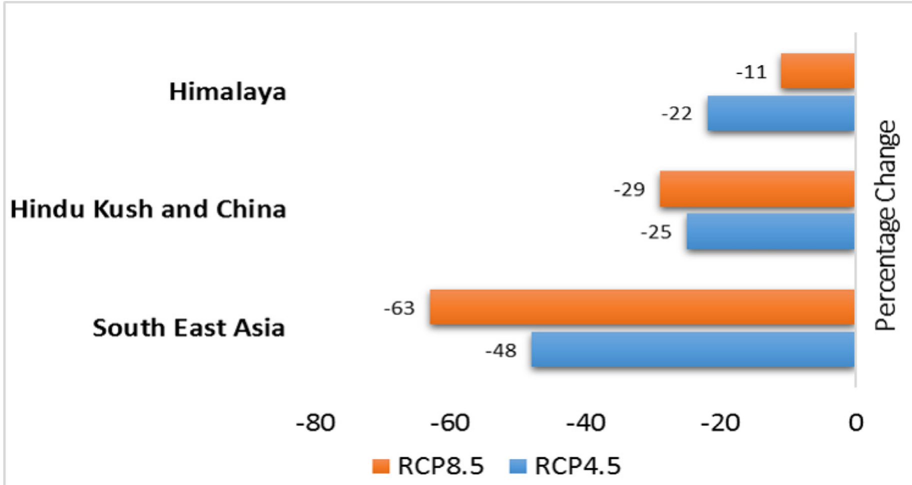

Fig. 9. Projected percentage change in the area of climatic niche for *Taxus wallichiana* under climate change scenarios.

4.3. Limitations of model

The results also vary as per the modelling approach (Thuiller, 2003). Integrating different approaches provides a robust prediction as compared to predictions done by individual rules (Araújo and New, 2007). Therefore, using ensemble modelling approach greatly enhances model outputs in terms of modelling rules. However, the parameterization of each model is essential to better fit the models. One of the best features of the ensemble model is the elasticity it allows to choose the best performing models based on testing scores (TSS, ROC).

The models developed in our study forecast the fundamental climatic niche (Austin, 2002) of the species rather than the realized niche (Silvertown, 2004). The later requires more input parameters, viz ecologically important life history traits, evolution and species dispersal behaviour that affect population growth and its spatial/geographical distribution and persistence. Another limitation of our study is the data deficiency which is a common issue with scarce and rare species.

Other topographic features such as elevation, slope etc. could not be included as predictor variables in the modelling procedures to give the species the opportunity to migrate under climate change. It is difficult to decide how much accurate the future climate projections are, or if one method is better than another, or which global climate model is the best. But the models we developed are the best available in so far as they provide an insight into the manifestations of climate change on *Taxus wallichiana* on such broad scale.

4.4. Recommendations for the conservation of Taxus wallichiana

The projected suitable areas under the various scenarios of climate change can be explored as areas for in situ conservation of *Taxus wallichiana* that cries for urgent measures of protection. Promoting the conservation of these areas could also help in preserving the entire ecosystem. In Indian parts of Himalaya, only 9 per cent of the climatic niche of *Taxus wallichiana* obtained in this study overlaps with the protected areas. Acknowledging the high socio-economic importance and number of environmental limitations of the species such as high susceptibility towards fire, low natural regeneration, slow growth, special measure of conservation efforts and strategy should be established. Research based on regeneration of Himalayan yew should be encouraged to carry off the burden from the wild populations of the species (Pant and Samant, 2008). Under the United Nations Convention on Biodiversity, the various stakeholders are in the process of enacting laws to limit the overuse/misuse of threatened medicinal plants that nature offers. Nonetheless, the species in question faces a highly complicated challenge of climate change impact that should be taken seriously into cognizance by implementing sound conservation measures and policies.

5. Conclusion

This study proposes a model of the climate change impacts on the potential climatic niche of *Taxus wallichiana*, using ensemble modelling under different climate change scenarios. The results show that a considerable loss in the suitable climatic envelopes for the species in question is likely, indicating that the projected climate change scenarios under IPCC AR5 may result in considerable changes in species population and distribution. Our study, therefore, provides an introductory baseline for assessing the impacts of climate change on one of the most charismatic Himalayan tree species, *Taxus wallichiana.* It highlights the threat that the species is facing from the global warming-driven climate change.

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